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(71) Applicant: CARDIAC PACEMAKERS, INC. [US/US]; 4100 Hamline Avenue North, St. Paul, MN 55112 (US).

(72) Inventors: SWEENEY, Robert, J.; 7853 Cobblestone Road, Woodbury, MN 55125 (US). LOVETT, Eric, G.; 1080 Lovell Avenue, Roseville, MN 55113 (US).

(74) Agent: VIKSNINS, Ann, S.; Schwegman, Lundberg, Woessner & Kluth, P.O. Box 2938, Minneapolis, MN 55402 (US).

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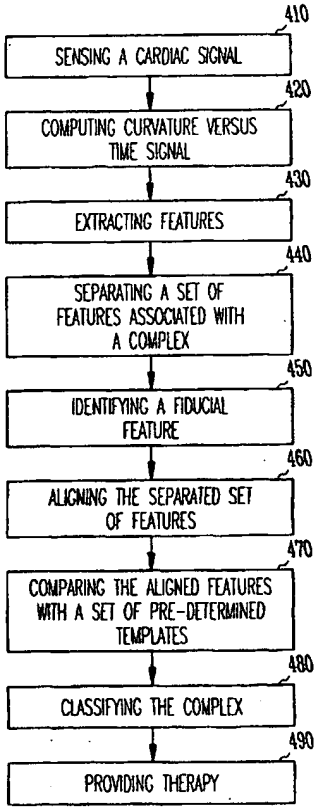
(54) Title: CURVATURE-BASED FEATURE SELECTION FOR ELECTROPHYSIOLOGIC SIGNALS



(57) Abstract: A method for curvature based complex identification and classification comprises sensing a cardiac signal and computing curvatures at sample points on the sensed cardiac signal, extracting features from the computed curvatures, comparing the extracted features with a set of predetermined templates, and classifying the sensed cardiac signal based on the outcome of the comparison.

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CURVATURE-BASED FEATURE SELECTION FOR ELCTROPHYSIOLOGIC SIGNALS

The present invention relates generally to cardiac rhythm management systems, and more particularly, it pertains to a system and method of classification and detection of cardiac signals.

Background of the Invention

Analysis of cardiac signals, which is routinely performed in electrocardiography is generally based on visual inspection to quantify or qualify wave morphology for the purpose of identifying and classifying abnormal patterns. Certain morphological characteristics of commonly recorded signals have high diagnostic value. The shape and inter arrival times of R-waves recorded in the electrocardiogram generally provide a wealth of information about the state of the heart. Accordingly, automated approaches for identifying and classifying abnormalities in signals such as cardiac signals have sought to use a signal's significant morphologic characteristics.

However, given the wide diversity of possible shapes for cardiac signals, it is usually not possible for an automatic approach to identify significant characteristics that can be used for unambiguous classification. Rather, automated classification approaches generally compare the entire morphological shape of a signal with the shape of similar signals with known abnormalities but without particular regard to the specific characteristics that the signals contain. Alternatively, automated classification approaches restrict the automated examination only to those signals which are essentially normal and use detailed metrics (for example QRS width, QT interval or ST segment amplitude) of the essentially normal morphology for classifying abnormalities.

Despite its importance in the analysis of biologic signals, the automated and accurate identification and quantification of the significant morphological characteristics (for example turns, peaks, knees, inflection points, and the like) in any cardiac signal (both abnormal as well as normal) is still in a developing stage. Existing methods have used the concept of sharpness (for example to

detect R-waves) but have had limited success. This is due in part to the overly simplistic mathematical treatment this concept has received, as reflected in the rudimentary algorithms used for these measurements. Most of the current detection methods rely on three point interpolations to measure sharpness. The simplest and most commonly used methods for measuring peaks of R-waves are based upon Taylor-series approximations to estimate the second derivative of the sensed signal. This formula utilizes highly local information (the point at the peak and its two close neighbors) ignoring nearby points which may contribute to signal peak. Other popular approaches utilize less local data, such as the peak and two adjacent extrema. All of these methods, which rely on three-point estimates of sharpness, may produce inaccurate estimates, if waveforms are complex or are contaminated with noise. Thus, a need exists for automated identification and classification of peaks, knees, inflection points, and the like in sensed cardiac signals that takes into account wave scale and complexity that can yield a more accurate estimate of peaks for identifying and classifying abnormalities in cardiac signals.

Summary of the Invention

The present subject matter provides a curvature based method of selecting features from electrophysiologic signals for purpose of complex identification and classification. According to one aspect of the present subject matter, this is accomplished by sensing a cardiac signal (sensing the cardiac signal includes sensing complexes continuously on a real-time basis) and computing curvatures on a sample point-by-sample point basis (X_1, X_2, X_3, ... X_I) on the sensed cardiac signal on a continuous basis. In one embodiment, the curvature at the sample points X_1, X_2, X_3, ... X_I are computed by fitting a cubic least square error curve (using N number of sample points) to the sensed cardiac signal. In this embodiment, N is an odd number, and the sample point (where the curvature is computed) is at a mid point of the N number of sample points.

Also on a continuous basis, features of significant interest are extracted from the computed curvatures. In some embodiments, this is accomplished by comparing the computed curvatures at the sample points X_1, X_2, X_3, ... X_I to a

set of predetermined threshold values. In some embodiments, the features are extracted based on computing features such as a time when the feature occurs, an amplitude of the feature, and other similar features at each of the sample points and comparing them to a set of threshold values.

Also on a continuous basis a set of features associated with a first complex in the sensed cardiac signal are identified and separated from the continuously computed and extracted features upon detecting a second subsequent complex. The second subsequent complex is a complex that is adjacent to the first complex and occurs substantially immediately after the first complex. This process of identifying and separating extracted features repeats itself from one sensed complex to another subsequent sensed complex on a real time basis. One reason for identifying and separating the set of features associated with the first complex is to prevent the features associated with the first complex from mixing with the features associated the second subsequent complex. Separating the features associated with first complex aids in classifying the sensed first complex.

Next, the process includes identifying a fiducial feature from the separated set of extracted features associated with the first complex and aligning the separated set of features with respect to the identified fiducial feature. In one embodiment, fiducial feature is identified based on comparing the times when each of the separated set of features occur with a time when a complex associated with the separated set of features is detected on the sensed cardiac signal, and selecting a feature from the separated set of features that is closest in time to the time when the complex associated with the separated set of features was detected. One reason for using a time when a complex is detected (such as R wave) in identifying the fiducial feature, is because the detection of a complex in a sensed cardiac signal is generally more reliable and consistent.

Next, the process includes aligning the separated set of features around the identified fiducial feature. Aligning the separated set of features around the identified fiducial feature aids in normalizing each of the separated set of feature around a datum such as the associated detected complex, and further aids in comparing the separated set of features with a set of predetermined templates.

Next the process includes comparing the aligned set of features to a set of predetermined templates to classify the associated complex. In some embodiments, the predetermined templates are a set of identified complexes associated with known cardiac arrhythmias that would assist in comparing and classifying the extracted set of features. In some embodiments, a therapy is provided to the heart based on the outcome of the classification. The above described process repeats itself on a continuous basis for a real-time classification of complexes from the sensed cardiac signal.

Other aspects of the invention will be apparent on reading the following detailed description of the invention and viewing the drawings that form a part thereof.

Brief Description of the Drawings

Figure 1 is a cardiac signal according to one aspect of the present invention.

Figure 2 is a curvature figure derived from the cardiac signal of Figure 1 according to one aspect of the present invention.

Figures 3A and 3B illustrate separating and aligning features derived from the curvature figure of Figure 2 according to one aspect of the present invention.

Figure 4 is a flow diagram illustrating generally one embodiment of operation of the present subject matter.

Figure 5 is a schematic/block diagram illustrating generally one embodiment of portions of a cardiac rhythm management system of the present subject matter.

Detailed Description

In the following detailed description, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that the embodiments may be combined, or that other embodiments may be utilized and that structural, logical and electrical changes may be made without departing from the spirit and scope of the present invention. The following detailed description is, therefore,

not to be taken in a limiting sense, and the scope of the present invention is defined by the appended claims and their equivalents.

Analysis of cardiac signals, which is routinely performed in electrocardiography is generally based on visual inspection to quantify or qualify wave morphology for the purpose of identifying and classifying abnormal patterns. Certain morphological characteristics of commonly recorded signals have high diagnostic value. The shape and inter arrival times of R-waves recorded in the electrocardiogram generally provide a wealth of information about the state of the heart. Accordingly, automated approaches for identifying and classifying abnormalities in signals such as cardiac signals have sought to use a signal's significant morphologic characteristics.

However, given the wide diversity of possible shapes for cardiac signals, it is usually not possible for an automatic approach to identify significant characteristics that can be used for unambiguous classification. Rather, automated classification approaches generally compare the entire morphological shape of a signal with the shape of similar signals with known abnormalities but without particular regard to the specific characteristics that the signals contain. Alternatively, automated classification approaches restrict the automated examination only to those signals which are essentially normal and use detailed metrics (for example QRS width, QT interval or ST segment amplitude) of the essentially normal morphology for classifying abnormalities.

Despite its importance in the analysis of biologic signals, the automated and accurate identification and quantification of the significant morphological characteristics (for example turns, peaks, knees, inflection points, and the like) in any cardiac signal (both abnormal as well as normal) is still in a developing stage. Existing methods have used the concept of sharpness (for example to detect R-waves) but have had limited success. This is due in part to the overly simplistic mathematical treatment this concept has received, as reflected in the rudimentary algorithms used for these measurements. Most of the current detection methods rely on three point interpolations to measure sharpness, may produce inaccurate estimates, if waveforms are complex or are contaminated with noise.

General System Overview

The present subject matter provides, among other things, a system of classifying a cardiac signal by computing a curvature versus time signal from a sensed cardiac signal and comparing the computed curvature versus time signal with a set of predetermined templates. The present system also provides an automated identification and classification of peaks, knees, inflection points, and the like in cardiac signals that takes into account wave scale and complexity that can yield a more accurate classification of cardiac signals.

The first step in the process includes computing continuously a curvature versus time signal from a sensed cardiac signal on a real-time basis. The process also includes extracting features (features are generally significant points of interest on the sensed cardiac signal) continuously on a real-time basis from the computed curvature versus time signal. Next, the process includes continuously separating a set of features associated with a first complex upon detecting a second subsequent complex so that each individual complex can be identified and classified on a real-time basis. Then the process includes aligning and classifying the extracted and separated set of features by comparing the separated set of features with a set of predetermined templates. Other aspects of the invention will be apparent on reading the following detailed description of the invention and viewing the drawings that form a part thereof.

Referring now to Figure 1, there is one embodiment of the first step in the process of sensing a cardiac signal 100 according to the present invention. Shown in Figure 1 are detection of heart beats associated with first and second complexes 110 and 120 at times 't_1' and 't_2' associated with the sensed cardiac signal 100 on a real-time basis on a time line 130. Also, shown on the time line 130 are the various sample points X_1, X_2, X_3, ... X_I used in computing a curvature versus time signal on the first complex 110. In the example embodiment shown in Figure 1, the sample points can be some fixed interval of time, such as 2, 4, 6... milliseconds, at which curvatures are computed on the sensed cardiac signal. Also shown in this embodiment, is the detection of the complexes (110, 120, and so on) on a continuous basis on the sensed cardiac signal 100.

Referring now to Figure 2, there is shown one embodiment of generating a curvature versus time signal 200 on a real-time basis derived from the sensed cardiac signal 100 shown in Figure 1 according to the present invention. Figure 2 is also on the same time line 130 as in Figure 1. Curvature figure 200 shown in Figure 2 is a computed curvature (expressed in time) versus time signal generated continuously by computing curvatures at the sample points X_1, X_2, X_3, ... X_I on the sensed cardiac signal 100 shown in Figure 1. Curvature figures 210 and 220 are computed curvature versus time signals associated with first and second complexes 110 and 120 shown in Figure 1, respectively. In this example embodiment, the curvature versus time signal is computed by overcoming the dimensionality of the curvature by changing the dimensionality of the curvature to time. The reason for overcoming the dimensionality of the curvature is to convert the time versus voltage signal, which is time versus curvature, to a time versus time signal to facilitate easier computation of curvature (for example, when a curve exists in length-length space, the quantity has dimension of length and is traditionally called the radius of curvature, and if the curve exists in time-time space, the analogous quantity will be called the radius of time). In this time-time space the curvature has a dimension of 1/Time. Also, shown in Figure 2 are some example sample points 230 at which curvatures are computed.

Referring now to Figures 3A and 3B, there is shown one example embodiment of extracting and aligning 300 sets of features associated with respective detected complexes. Figure 3A, illustrates continuously extracting features 320 from the computed curvature versus time signal 200 shown in Figure 2. Also shown in this example embodiment, are some sample times in milliseconds 330 when the extracted features occur on the time line 130. Figure 3A is also on the same time as that of Figures 1 and 2. In the example embodiment shown in Figure 3A, the sample times (where the curvatures are computed) have a fixed interval of 2 milliseconds. Also, in this example embodiment, the beat associated with first complex 110 is detected at 11 milliseconds (t_1) and the beat associated with the second subsequent complex 120 is detected at 101 milliseconds (t_2).

Figure 3B shows separating sets of extracted features 310 associated with the complexes 110, 120 ... on a continuous basis from the continuously extracted features 320 shown in Figure 3A. In the example embodiment shown in Figure 3B, a set of features 340 associated with first complex is separated upon detecting the second subsequent complex 120. Also shown are separating a set of features 350 associated with second complex upon detecting a third subsequent complex. This process of separating a set of features associated with a complex is done on a continuous basis. Features associated with first complex are separated from the features of subsequent second complex in order to (so that the features are not mingled with the extracted features of the second subsequent complex) classify the sensed first complex 110. The next step is to identify fiducial features 360, 370, and so on. In the example embodiment shown in Figure 3B, fiducial feature 360 is identified based on comparing times when the separated sets of extracted features associated with the first complex 110 occur with a time when the heart beat associated with the first complex 110 is detected ('t_1'), and choosing a feature from the set of features 340 that is closest in time to the time when the heart beat associated with the first complex 110 is detected. In the example shown in Figure 1, the first complex 110 is detected at 11 milliseconds. The times when the separated set of features 340 associated with the first complex 110 occur are 2, 4, 8, 10, 12, 14, 20, and 24 milliseconds as shown in Figure 3A. Based on comparing the times when the separated set of features 340 occur with the time when first complex 110 was detected, the feature 360 that occurs at a time of 10 milliseconds is the closest in time to the detected first complex 110 which occurs at 11 milliseconds. Therefore, extracted feature 360 is selected as the fiducial feature from the separated set of features 340 associated with the first complex 110. Similarly, the extracted feature 370 is selected as the fiducial feature for the separated set of features 350 associated with subsequent second complex 120. This process repeats itself continuously on a real time basis. In some embodiments, the fiducial feature is identified from the set of separated features associated with the first complex based on a predetermined deviation value. The predetermined deviation value is based on a sample point having an amplitude farthest from a predetermined reference point.

The next step is to align the separated set of features 340 associated with the first complex 110, and to classify the separated set of features 340 by comparing the aligned set of features with a set of templates. Separated sets of features 340 and 350 are aligned to normalize the separated sets of feature 340 and 350 so that the aligned features aid in comparing the separated sets of features with a template to classify the sensed complexes 110 and 120. Figure 3B illustrates one example embodiment of aligning the set of extracted features 340 (associated with first complex 110) with respect to an identified fiducial feature 360. In this example embodiment, the time when the identified fiducial feature occurs (at 10 milliseconds) is subtracted from each of the times when the separated set of features 340 associated with the first complex 110 occurs (at 2, 4, 8, 10, ... milliseconds) to arrive at aligned times -8, -6, -2, 0, 2, 4, 10, and 14 milliseconds for the separated set of features 340. Similarly, the aligned times -8, -2, 0, 2, 4, and 10 are computed for the separated set of features 350 associated with the second complex 120. This process of aligning separated set of features continues on a real time basis for the detected complexes on the sensed cardiac signal 100. It can be seen from the above illustrated computation, that the process aligning helps normalize the times associated with each of the separated sets of features, and how it aids in comparing the separated set of features 340 and 350 with a set of templates and in classifying the sensed complexes 110 and 120.

Figure 4 illustrates a method 400 of identifying and classifying a sensed cardiac signal on a real-time basis. Method 400, as shown in Figure 4, begins with step 410 by sensing a cardiac signal 410 from the one or more electrodes disposed in or around a heart 515 on a continuous basis.

The next step 420 in the process comprises computing curvatures at sample points X_1, X_2, X_3, ... X_I on the sensed cardiac signal. In some embodiments, the sample points X_1, X_2, X_3, ... X_I are fixed intervals of time at which the sensed cardiac signal is computed for its curvature. The sensed cardiac signal can be an atrial or ventricular signal of a heart. In one embodiment, the curvatures at sample point X_1, X_2, X_3, ... X_I is computed by fitting a cubic least square error curve to the sensed cardiac signal by using N sample points. In

this embodiment, N is an odd number greater than or equal to 5. Also in this embodiment, the cardiac rhythm management system computes the curvature at a mid point of the N sample points. In one embodiment, the cardiac rhythm management system computes curvature (K) at a sample point X_I on the cardiac signal by using 5 sample points over which the cubic fit is (N being 5 in this example) made using

$$K = (2C_I/(1+B_I^2)^{3/2})$$

where

$$B_I = T_1Y(I-2) + T_2Y(I-1) + T_3Y(I) + .T_4Y(I+1) + T_5Y(I+2)$$

$$C_I = S_1Y(I-2) + S_2Y(I-1) + S_3Y(I) + S_4Y(I+1) + S_5Y(I+2)$$

where S_1, S_2, S_3 ... and T_1, T_2, T_3 ...are constant terms in the summation. In this embodiment, I corresponds to the sample point at which the curvature is being computed. For example, if the sample point is X_3, then I will be equal to 3 and so on.

In another embodiment, the system computes average curvature between two adjacent sample points by using a linear interpolation of the B_I and C_I between the two adjacent sample points (this is done by doing the integral of the curvature between the two adjacent sample points). This integration helps capture any curvatures that become larger between the two adjacent sample points, so that the point-wise curvature values may more robustly represent the curvatures in the sensed cardiac signal. The system also integrates curvature versus time curve to find the area under the curve. This area under the curve represent the total change in angle between two points on the original cardiac signal. Thus, peaks, turns, inflections, and the like in the cardiac signals can be identified when the curvature versus time curve has peaks or nadirs. These peaks and nadirs denote points along the sensed cardiac signal where the turns are locally sharpest. Also, slow but steady turns on the sensed cardiac signal can be characterized by a small peak having a substantial area under the curvature curve. Thus, integrating curvatures between two adjacent sample points can help capture any curvatures that may become larger between any two adjacent sample points.

In one embodiment, the cardiac rhythm management system computes curvatures at sample points X_1, X_2, X_3, ... X_I on the sensed cardiac signal on a continuous basis.

Then the next step 430 in the process includes extracting features from the computed curvatures by comparing the computed curvatures with a set of predetermined threshold values. Figure 3A, illustrates extracting features from the computed curvatures at the sample points X_1, X_2, X_3, ... X_I. In some embodiments, the set of predetermined threshold values are based on a previous curvature value, a first curvature value, and a curvature threshold limit. In one embodiment, the step of extracting features from the curvature versus time signal is done on a continuous basis on the sensed cardiac signal as shown in Figure 3A. In some embodiments, the features are defined by one or more metrics. In this embodiment, the one or more metrics are defined as area under a computed curvature, a time of centroid of the area, and a value of original signal amplitude at a time of centroid of the area associated with the feature.

Then the next step 440 comprises separating a set of features associated with a first complex upon detecting a second subsequent complex from the sensed cardiac signal. Separating of extracted features associated with the detected complex is illustrated in detail Figures 1, 2, 3A and 3B. In some embodiments, the second subsequent complex is detected based on continuously processing the sensed cardiac signal to produce a signal that is the absolute value of the first derivative of a sensed cardiac signal versus time. Then comparing the produced absolute value versus time signal with a predetermined decaying threshold value to detect an occurrence of the second subsequent complex. In some other embodiments, the second subsequent complex is detected when the absolute value of the first derivative exceeds a predetermined decaying threshold value. In some embodiments, the features associated with the first complex are stored in a memory until the second subsequent complex is detected, and at that point, the features associated with the first complex are replaced by the features associated with the second subsequent complex in the memory. The step of separating can comprise separating the set of features based on selecting features associated with the first complex having a predetermined time earlier than the

detected second subsequent complex. In some embodiments, each of the set of features are further compared to an area threshold value to eliminate features less than the area threshold value. This can result in a set of revised features that can represent the first complex.

Then the next step 450 in the process is to identify a fiducial feature from the set of separated features associated with the first complex based on a predetermined deviation value. In some embodiments, fiducial feature is identified based on comparing the time when the first complex occurs with the times when the separated set of features associated with the first complex occur. The process of identifying a fiducial feature is discussed in more detail with respect to Figures 3A and 3B.

Then the next step 460 in the process comprises aligning the set of separated features with respect to the identified fiducial feature. The process of aligning is also discussed in more detail in Figure 3B. The process of aligning helps normalize the times associated with each of the separated set of features and further facilitates in comparing the separated set of features with a set of predetermined templates to classify the detected complex.

Then the next step 470 comprises comparing the aligned set of separated features with a set of predetermined templates. In one embodiment, the set of predetermined templates are one or more known types of heart beat signals. In another embodiment, the set of predetermined templates consists of sets of template boxes or zones for each of the known types of heart beat signals. Generally, each template box or zone can have center amplitude, a time width, and an amplitude width. Also generally, the template boxes or zones for each known type of heart beat can consist of one or more template boxes or zones each of which can have different centers and widths. In this embodiment, the comparing step comprises assigning a score based on how well each feature matches with each of the set of template boxes or zones. In this embodiment, if the separated set of features associated with the first complex fails to match with the set of templates then the complex is assigned with an unknown heart beat classification. In one embodiment, the set of template boxes or zones are modified over time to reflect any changes in sets of separated features used in

matching with the template boxes or zones. This can permit known beat type templates to follow slow trends or long-term changes in the cardiac signal.

The next step 480 in the process comprises classifying the detected first complex based on the outcome of the comparison. Then the next step 490 comprises providing a therapy based on the outcome of the classification. In one embodiment, the next step includes guiding a therapy to a heart based on the outcome of the classification. In another embodiment, the next step in the process includes storing classifications for future diagnostic purposes.

Figure 5 is a schematic/block diagram 500 illustrating one embodiment of portions of a cardiac rhythm management system 505, which is coupled to a heart 515. Cardiac rhythm management system 505 includes a power source 580, a controller 540, a sensing circuit 520, a therapy circuit 590, and a via node/bus 530. The sensing circuit 520 is coupled by a lead 510 to the heart 515 for receiving, sensing, and or detecting electrical heart signals. The sensing circuit 520 provides one or more sensed cardiac signals to the controller 540, via the node/bus 530. The controller 540 also controls the delivery of a therapy provided by the therapy circuit 590 and/or other circuits, as discussed below.

The controller 540 includes various modules, which are implemented either in hardware or as one or more sequences of steps carried out on a microprocessor or other controller. Such modules are illustrated separately for conceptual clarity; it is understood that the various modules of the controller 540 need not be separately embodied, but may be combined and/or otherwise implemented, such as in software/firmware.

In general terms, the sensing circuit 520 senses a cardiac signal on a continuous basis from a heart tissue in contact with a catheter lead 510 to which the sensing circuit 520 is coupled. In one embodiment, the sensed cardiac signal is an atrial signal. In another embodiment, the sensed cardiac signal is a ventricular signal. Sensed cardiac signal from the sensing circuit 520 is then received and processed by an analyzer 550 of the controller 540 to compute curvatures continuously on a real-time basis at sample point X_1, X_2, X_3, ... X_I on the sensed cardiac signal. In some embodiments, the sample points are spaced at fixed intervals of time preset by the analyzer 550 on the sensed cardiac signal.

In one embodiment, the analyzer 550 computes curvature at sample points X_1, X_2, X_3, ... X_I by fitting a cubic least square error curve to the sensed cardiac signal using N sample points to fit the cubic least square error curve. In one embodiment, the analyzer 550 computes the computing curvature (K) at a sample point X_I on the cardiac signal when using 5 sample points over which the cubic fit is (N being 5 in this example) made using

$$K = (2C_I/(1+B_I^2)^{3/2})$$

where

$$B_I = T_1Y(I-2) + T_2Y(I-1) + T_3Y(I) + T_4Y(I+1) + T_5Y(I+2)$$

$$C_I = S_1Y(I-2) + S_2Y(I-1) + S_3Y(I) + S_4Y(I+1) + S_5Y(I+2)$$

where S_1, S_2, S_3 ... and T_1, T_2, T_3 ...are constant terms in the summation. In this example embodiment, I is equal to the point at which the curvature is being computed. For example, if the curvature is being computed at sample point X_3, then I will be equal to 3 and so on. In one embodiment, N is an odd number greater than or equal to 5. In this embodiment, the analyzer 550 computes curvature at a midpoint of the N number of sample points.

In another embodiment, the analyzer 550 computes curvature based on an average curvature between two adjacent sample points based on a linear interpolation of the B_I and C_I between two adjacent points (integrating the computed curvatures between the two adjacent sample points). In one embodiment, the analyzer 550 computes the curvatures continuously on a real-time basis from the sensed cardiac signal. Then the analyzer 550 extracts features by comparing the computed curvatures to a set of predetermined threshold values. In one embodiment, the predetermined threshold values are based on a previous curvature value, a curvature value, and a curvature threshold limit. In one embodiment, the analyzer 550 extracts features on a continuous basis. Then the analyzer 550 separates a set of features associated with a first complex upon detecting a second subsequent complex from the sensed cardiac signal. Then the analyzer 550 identifies a fiducial feature from the set of separated features associated with the first complex based on a predetermined deviation value. Then the analyzer 550 further aligns the set of separated features with respect to the identified fiducial feature. In one embodiment, the analyzer 550 separates the

set of features associated with the first complex based on a predetermined time earlier than the detected second subsequent complex. In one embodiment, the predetermined deviation value is based on a sample point having an amplitude farthest from a predetermined reference point.

Then a comparator 570 coupled to the analyzer 550, compares the aligned set of features associated with the first complex with a predetermined set of templates, and classifies the first complex based on the outcome of the comparison. In one embodiment, the comparator 570 issues a command signal based on the outcome of the classification. In another embodiment, the therapy circuit 590 coupled to the comparator 570 delivers the electrical energy through the lead 510 to at least one electrode disposed in or around the heart 515 upon receiving the command signal from the comparator 570. The electrical energy delivered by the therapy circuit 590 can be a pacing pulse electrical energy. In one embodiment, the analyzer 550 includes a variable gain circuitry that can adapt according to the changes in the sensed cardiac signal. In one embodiment, the controller 540 includes a memory 560 coupled to the comparator 570 and the analyzer 550 to store the extracted features of the first complex. In another embodiment, the memory 560 stores the classified first complexes for diagnostic purposes.

It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiments will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

Conclusion

The above described method provides, among other things, a curvature based complex identification and classification. The process comprises sensing a cardiac signal and computing curvatures at sample points on the sensed cardiac signal, extracting features from the computed curvatures, comparing the extracted features with a set of predetermined templates, and classifying the cardiac signal based on the outcome of the comparison.

WHAT IS CLAIMED IS:

1. A cardiac rhythm management system, comprising:

at least one electrode;

a signal sensing circuit coupled to the electrode to sense a cardiac signal;

a controller coupled to the sensing circuit, wherein the controller receives the sensed cardiac signal, and wherein the controller includes:

an analyzer, to compute curvatures at sample points X_1, X_2, X_3, ... X_I on the sensed cardiac signal, wherein the analyzer extracts features by comparing the computed curvatures to a set of predetermined threshold values; and

a comparator, coupled to the analyzer, compares the extracted features with a set of predetermined templates, and classifies the sensed cardiac signal based on the outcome of the comparison.

2. The system of claim 1, wherein the sensing the cardiac signal includes sensing complexes on a real-time basis, wherein the complexes comprise heart beat signals.

3. The system of any of the preceding claims, wherein computing curvatures comprises computing curvatures at the sample points X_1, X_2, X_3, ... X_I by fitting a cubic least square error curve to a first complex of the sensed cardiac signal using an N sample points to fit the cubic least square error curve, wherein the analyzer extracts features of the first complex by comparing the computed curvatures of the first complex to a set of predetermined threshold values, and wherein the analyzer further separates a set of features associated with the first complex upon detecting a second subsequent complex from the sensed cardiac signal; and wherein the comparator compares the aligned set of features associated with the second subsequent complex with a set of predetermined templates, and classifies the first complex based on the outcome of the comparison.

4. The system of any of the preceding claims, wherein the comparator issues a command signal based on the outcome of the classification.

5. The system of any of the preceding claims further comprises a therapy circuit, coupled to the comparator, to deliver electrical energy through the at least one electrode upon receiving the command signal from the comparator.

6. The system of claim 5, wherein the electrical energy is a pacing pulse electrical energy.

7. The system of claim 3, wherein the set of predetermined threshold values are based on a previous curvature value, a curvature value, and a curvature threshold limit.

8. The system of claim 3, wherein the analyzer further identifies a fiducial feature from the set of separated features associated with the first complex based on a predetermined deviation value, and further aligns the set of separated features associated with the first complex with respect to the identified fiducial feature.

9. The system of claim 8, wherein the analyzer separates the set of features associated with a first complex based on a predetermined time earlier than the detected second subsequent complex.

10. The system of claim 9, wherein the predetermined deviation value is based on a sample point having an amplitude farthest from a predetermined reference point.

11. The system of claim 3, wherein N is an odd number greater than or equal to 5.

12. The system of claim 11, wherein the computing curvature comprises computing curvature at a mid point of the N number of sample points.

13. The system of claim 12, wherein the analyzer computes the curvature (K) at a sample point X_I on the cardiac signal when using 5 sample points to fit the cubic least square error curve, based on

$$K = (2C_I/(1+B_I^2)^{3/2})$$

where

$B_I = T_1Y(I-2) + T_2Y(I-1) + T_3Y(I) + .T_4Y(I+1) + T_5Y(I+2)$

$C_I = S_1Y(I-2) + S_2Y(I-1) + S_3Y(I) + S_4Y(I+1) + S_5Y(I+2)$

where S and T are constants.

14. The system of claim 13, wherein the analyzer computes an average curvature between two adjacent sample points based on linear interpolation of the B_I and C_I between two adjacent points and integrating the computed curvatures between the two adjacent sample points.

15. The system of any of the preceding claims, wherein the analyzer further comprises a variable gain, wherein the variable gain adapts according to changes in the sensed cardiac signal.

16. The system of any of the preceding claims, wherein the at least one electrode is disposed in or around a heart.

17. The system of any of the preceding claims further comprises a memory to store the extracted features of the first complex.

18. The system of claim 17, wherein the memory further stores the classified first complexes for diagnostic purposes.

19. A method, comprising:

sensing a cardiac signal;

computing curvatures at sample points X_1, X_2, X_3, ... X_I on the sensed cardiac signal;

extracting features from the computed curvatures;

comparing the extracted features with a set of predetermined templates; and

classifying the cardiac signal based on an outcome of the comparison.

20. The method of claim 19, wherein the cardiac signal comprises sensing complexes in real time, wherein the complexes are cardiac cycles.

21. The method of any of the preceding claims, wherein computing the curvatures at sample points X_1, X_2, X_3, ... X_I comprises computing curvatures at the sample points X_1, X_2, X_3, ... X_I by fitting a cubic least square error curve to sensed complexes on the cardiac signal, wherein the sample points have a predetermined interval of time between adjacent sample points.

22. The method of claim 21, wherein computing the curvatures at sample points X_1, X_2, X_3, ... X_I comprises fitting a cubic least square error curve around a sample point by using N number of sample points to fit the cubic least square error curve, wherein N is an odd number greater than or equal to 5.

23. The method of claim 22, wherein computing the curvature at the sample point using the N number of sample points comprises using the sample point as a mid point of the N number of sample points.

24. The method of claim 23, wherein computing the curvature (K) at a sample point X_I of the cardiac signal when using 5 sample points to fit the cubic least square error curve, is based on

$$K = (2C_I/(1+B_I^2)^{3/2})$$

where

$$B_I = T_1Y(I-2) + T_2Y(I-1) + T_3Y(I) + .T_4Y(I+1) + T_5Y(I+2)$$

$$C_I = S_1Y(I-2) + S_2Y(I-1) + S_3Y(I) + S_4Y(I+1) + S_5Y(I+2)$$

where S and T are constants.

25. The method of claim 24, wherein computing the curvature comprises computing an average curvature between two adjacent sample points based on a linear interpolation of the B_I and C_I between two adjacent points and integrating the computed curvatures between the two adjacent sample points X_1, X_2, X_3, ... X_I.

26. The method of any of the preceding claims, wherein extracting features from the computed curvatures includes:

comparing the computed curvatures to a set of predetermined threshold values; and

identifying and separating a set of extracted features associated with a first complex upon detecting a second subsequent complex from the sensed cardiac signal.

27. The method of claim 26, wherein the set of predetermined threshold values are based on a previous curvature value, a first curvature value, and a curvature threshold limit.

28. The method of claim 27, wherein separating the set of extracted features comprises separating the set of features based on identifying features associated with the first complex having a predetermined time earlier than the detected second subsequent complex.

29. The method of any of the preceding claims, wherein comparing the extracted features comprises comparing the separated set of extracted features associated with the first complex with a set of predetermined templates.

30. The method of any of the preceding claims, wherein comparing the extracted features further comprises:

identifying a fiducial feature from the set of separated features associated with the first complex based on a predetermined deviation value; and

aligning the set of separated features associated using the identified fiducial feature.

31. The method of claim 30, wherein the predetermined deviation value is based on a sample point having an amplitude farthest from a predetermined reference point.

32. The method of any of the preceding claims further includes repeating the above steps for a real-time classification of heart beat signals from the sensed cardiac signal.

33. The method of claim 31, wherein the feature is defined by one or more metrics.

34. The method of claim 33, wherein the one or more metrics are area under a computed curvature, a time of centroid of the area, and a value of original signal amplitude at a time of the centroid of the area.

35. The method of claim 31, wherein comparing the set of features comprises comparing the set of features associated with the first complex with one or more predetermined heart beat signals.

36. The method of claim 26, wherein the predetermined set of templates comprises one or more predetermined template zones defined by a center time, a center amplitude, a time width, and an amplitude width.

37. The method of any of the preceding claims further comprises providing a therapy to a heart based on the outcome of the classification.

38. The method of any of the preceding claims further comprises guiding a therapy to a heart based on the outcome of the classification.

39. The method of any of the preceding claims further comprises storing classifications for diagnostic purposes.

40. The method of any of the preceding claims, wherein computing the curvature further comprises permitting the computed curvature signal to have a variable gain that adapts according to the changes in sensed cardiac signal.

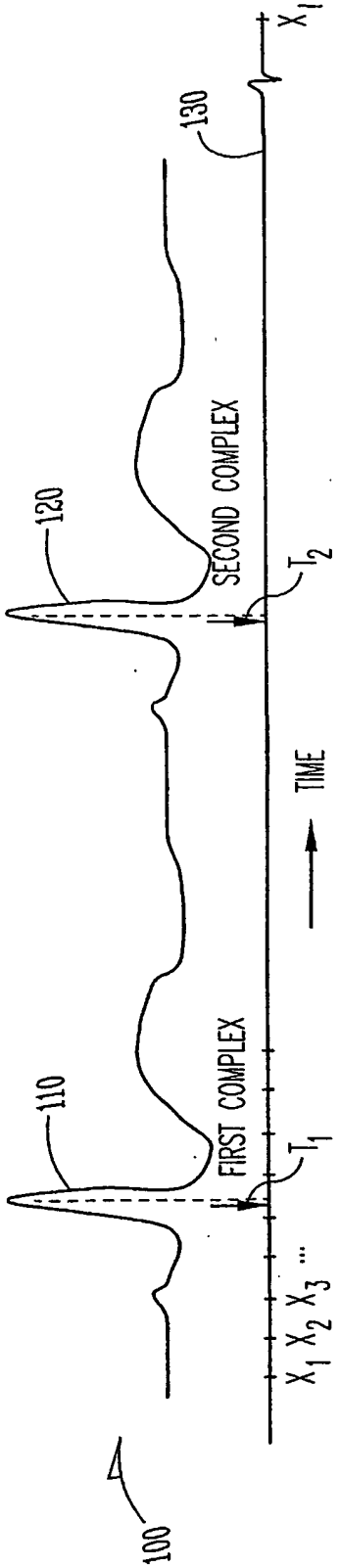

100
110
120
130
FIRST COMPLEX
SECOND COMPLEX
T_1
T_2
TIME
X_1
X_1 X_2 X_3 ...

Fig. 1

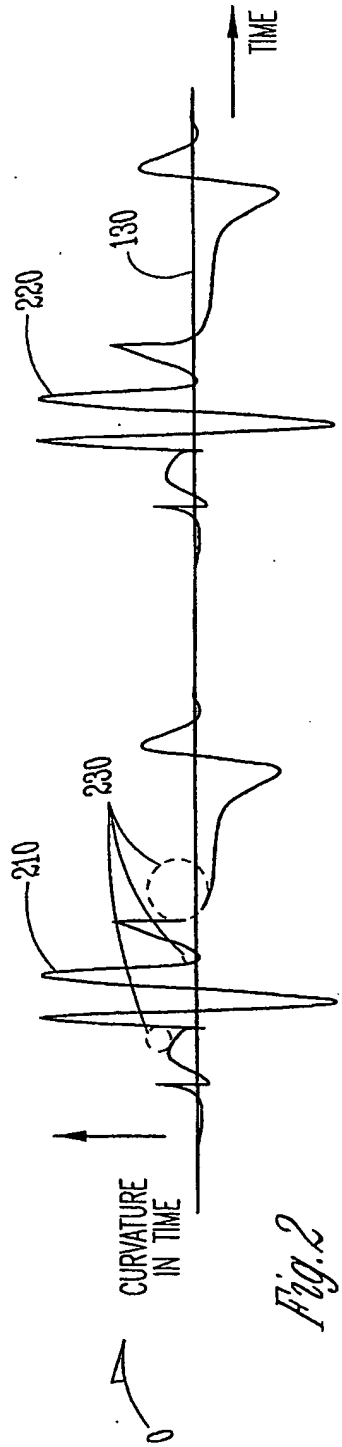
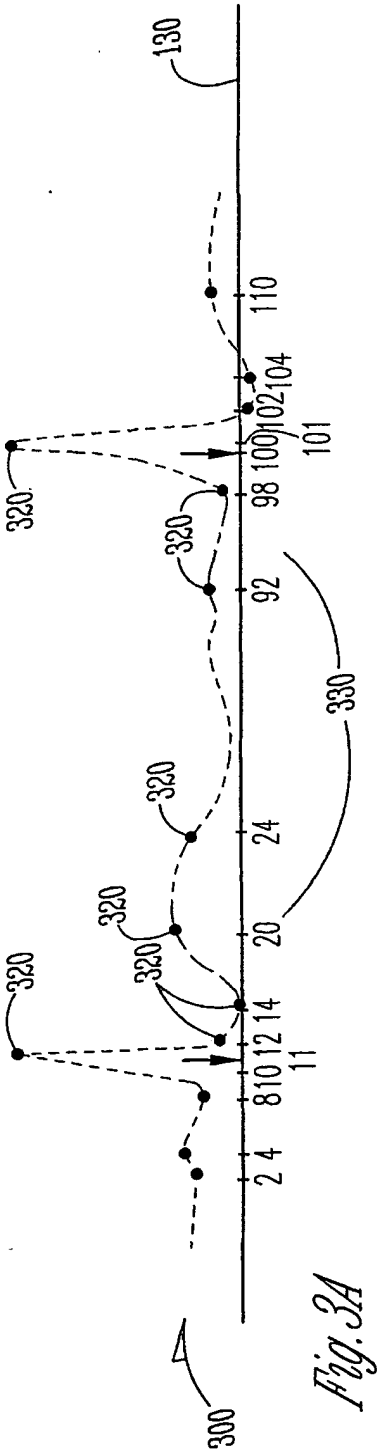

0
CURVATURE IN TIME
TIME
210
220
230
130

Fig. 2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110
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102
101
100
98
92
330
320
24
20
14
12
11
10
8
4
2
300

Fig. 3A

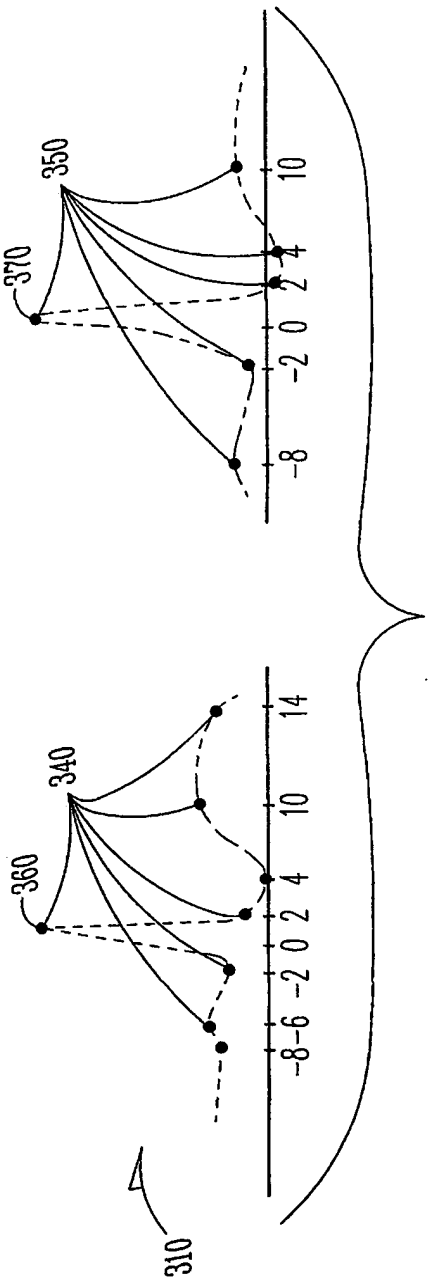
350
370
10
4
2
0
-2
-8
340
360
14
10
4
2
0
-2
-6
-8
310

Fig. 3B

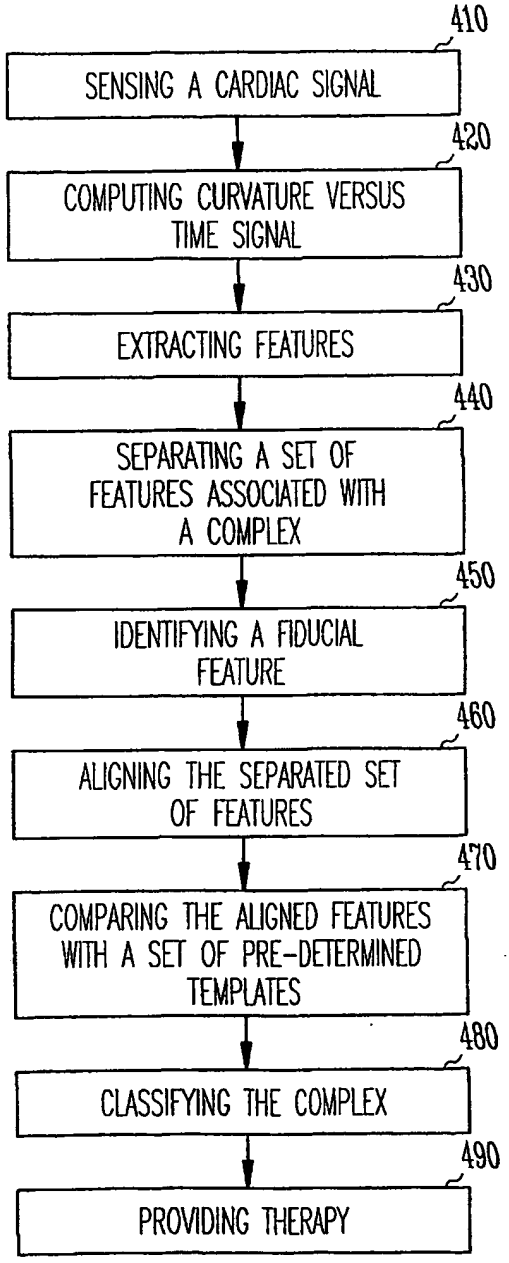
400
410
SENSING A CARDIAC SIGNAL
420
COMPUTING CURVATURE VERSUS TIME SIGNAL
430
EXTRACTING FEATURES
440
SEPARATING A SET OF FEATURES ASSOCIATED WITH A COMPLEX
450
IDENTIFYING A FIDUCIAL FEATURE
460
ALIGNING THE SEPARATED SET OF FEATURES
470
COMPARING THE ALIGNED FEATURES WITH A SET OF PRE-DETERMINED TEMPLATES
480
CLASSIFYING THE COMPLEX
490
PROVIDING THERAPY

Fig. 4

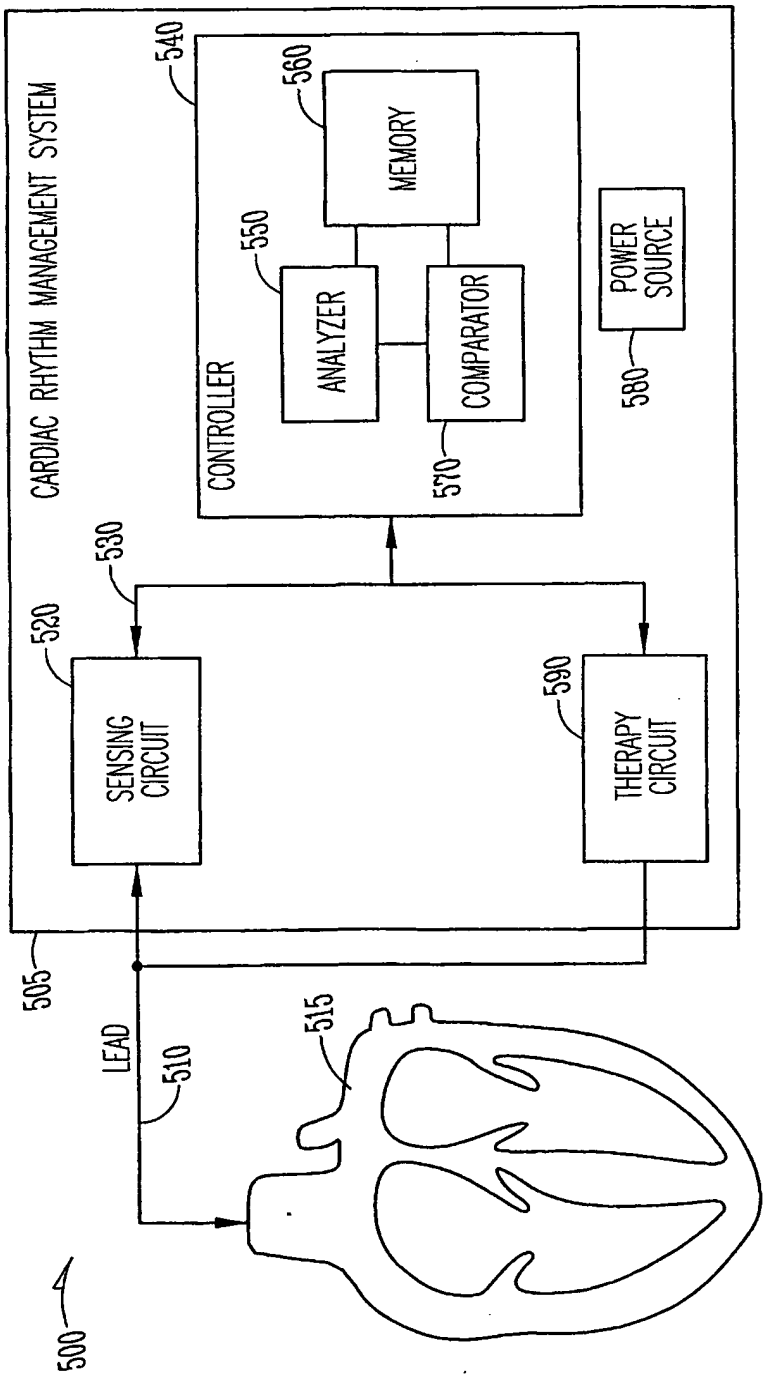
CARDIAC RHYTHM MANAGEMENT SYSTEM
CONTROLLER
MEMORY
ANALYZER
COMPARATOR
POWER SOURCE
SENSING CIRCUIT
THERAPY CIRCUIT
LEAD
500
505
510
515
520
530
540
550
560
570
580
590

Fig. 5

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(71) Applicant: CARDIAC PACEMAKERS, INC. [US/US]; 4100 Hamline Avenue North, St. Paul, MN 55112 (US).

(72) Inventors: SWEENEY, Robert, J.; 7853 Cobblestone Road, Woodbury, MN 55125 (US). LOVETT, Eric, G.; 1080 Lovell Avenue, Roseville, MN 55113 (US).

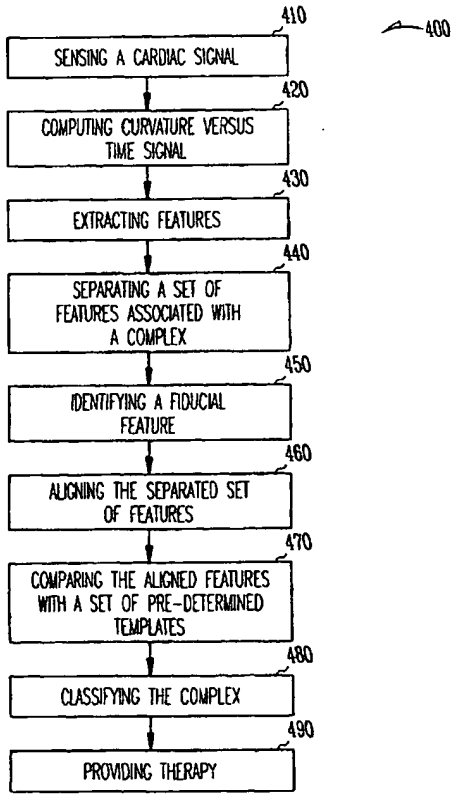
(74) Agent: VIKSNINS, Ann, S.; Schwegman, Lundberg, Woessner & Kluth, P.O. Box 2938, Minneapolis, MN 55402 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: CURVATURE-BASED FEATURE SELECTION FOR ELECTROPHYSIOLOGIC SIGNALS



(57) Abstract: A method for curvature based complex identification and classification comprises sensing a cardiac signal and computing curvatures at sample points on the sensed cardiac signal, extracting features from the computed curvatures, comparing the extracted features with a set of predetermined templates, and classifying the sensed cardiac signal based on the outcome of the comparison.

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Published:
— *with international search report*

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16 January 2003

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 01/45763

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 A61N1/37 A61B5/0452 G06F17/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 A61N A61B G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99 65570 A (CARDIAC PACEMAKERS) 23 December 1999 (1999-12-23) the whole document ---	1,2,4-6, 16-18
X	WO 00 47278 A (CARDIAC PACEMAKERS) 17 August 2000 (2000-08-17) the whole document ---	1,2,4-6, 16-18
X	EP 0 554 208 A (INCONTROL INC) 4 August 1993 (1993-08-04) the whole document in particular column 16, line 26 -column 17, line 28 column 22, line 18 -column 23, line 10 --- -/--	1,2,4, 16-18

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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Date of the actual completion of the international search	Date of mailing of the international search report
26 August 2002	03/09/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Ferrigno, A

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INTERNATIONAL SEARCH REPORT

Int...onal Application No
PCT/US 01/45763

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WO 00 10455 A (VACHTSEVANOS GEORGE ;ECHAUZ JAVIER (US); ESTELLER ROSANA (US); LIT) 2 March 2000 (2000-03-02) page 17, line 29 -page 18, line 11	1

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 01/45763

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.: 19-40
because they relate to subject matter not required to be searched by this Authority, namely:

Rule 39.1(iv) PCT - Diagnostic method practised on the human or animal body

2. [ ] Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest.

[ ] No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 01/45763

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		WO 0010455 A1	02-03-2000